CFD STUDY ON THE EFFECT OF VELOCITY AND TEMPERATURE TOWARD THE PERFORMANCE ON PARTIAL COMBUSTION UNIT

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ABSTRACT

In the iron and steel making process, Direct Reduction Plant (DRP) is the most important components which are consist of Partial Combustion Unit (PCU). PCU take place in between the process gas heater and the oxides removal reactor. The PCU consists of one transfer line and two oxygen lances. On the oxygen lances, there is a nozzle attached to each of it. The simulation via Computation Fluid Dynamics (CFD) to validate the performance of the PCU with current installation by analyzing the profile of the temperature was performed using standard k-ε (SKE) viscous model and Eddy Dissipation (ED) turbulence-chemistry interaction model. The heated natural gas (NG) from the heater will be supplied to the transfer line. The performance of PCU using current process was compared with the new process scheme which consists of different mass fraction of the process gasses, temperature and velocity of process gasses and oxygen to identify the most effective process in term of the temperature used in PCU by using CFD. The simulation also was performed to detect either the boundary refractory in the simulation will influence the temperature profile obtain. These should be design using GAMBIT 2.4 and simulation should be run to compute the solution using FLUENT 6.3.26. From this study, the new process scheme show the temperature profile at the validation point is high compare to the current process scheme even though the percentage error is much higher in the new process scheme compare to current process scheme. Thus, further study on design and data modification should be done to get more accurate result.

ABSTRAK

Dalam proses penghasilan besi dan keluli, 'Direct Reduction Plant' (DRP) adalah salah satu komponen penting yang terdiri daripada Unit Pembakaran Separa (PCU). PCU ini terletak di antara pemanas proses gas dan reaktor penyingkiran oksida. Di dalam PCU ini terdapat satu 'transfer line' dan dua 'oxygen lances'. Terdapat satu 'nozzle' pada setiap satu 'oxygen lances' tersebut. Simulasi yang di jalankan menggunakan alatan pengkomputeran 'Computation Fluid Dynamics' (CFD) adalah untuk membandingkan prestasi PCU dengan pelan sebenar dengan menganalisis penghasilan haba dengan mengunakan 'standard k-ε' (SKE) model kelikatan dan Eddy Dissipation (ED) model pergolakan interaksi kimia. Gas asli (NG) yang telah di panaskan di dalam pemanas akan di salurkan ke dalam 'transfer line'. Prestasi PCU yang menggunakan proses semasa dibandingkan dengan yang menggunakan proses yang mempunyai perbezaan dalam percahan jisim proses gas, suhu dan halaju proses gas dan oksigen untuk mengetahui proses yang efektif dengan membandingkan suhu yang terhasil di dalam PCU dengan menggunakan CFD. Simulasi ini juga di lakukan untuk melihat kesan modifikasi terhadap reka bentuk dengan penambahan 'boundary refractory'. Reka bentuk 'transfer line' ini harus di lukis menggunakan GAMBIT 2.4 dan simulasi di jalankan untuk mendapatkan keputusan menggunakan FLUENT 6.3.26. Menerusi keputusan yang di perolehi, proses baru menunjukkan peningkatan suhu yang ketara pada titik yang mempunyai 'thermocouple' benbanding dengan proses semasa yang menunjukkan peningkatan yang sedikit walaupun peratusan ralat proses baru lebih tinggi daripada proses semasa. Justeru itu, modifikasi terhadap data dan reka bentuk sepatutnya di jalankan demi untuk mendapat keputusan yang memberangsangkan.

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LIST OF SYMBOLS

k	Turbulence kinetic energy
ε	Dissipation rate
G_k	Generation of turbulence kinetic energy due to the mean velocity gradients
G_b	Generation of turbulence kinetic energy due to buoyancy
P_{rt}	Prandtl number for energy
g_i	Component of the gravitational vector in the i^{th} direction
β	Thermal expansion coefficient
Y_M	Contribution on fluctuation dilatation in compressible turbulence to the overall dissipation rate
M_t	Turbulence mach number
α	Speed of sound
Y_i	Mass fraction of each species i^{th} species
R_i	Net rate of production by chemical reaction
S_i	Net rate of creation by addition from the dispersed phase
$R_{i,r}$	Net rate of production of species i due to reaction r
Y_p	Mass fraction of any products species P
Y_R	Mass fraction of particular reactant R
k_{eff}	Effective thermal conductivity
E	Total energy
$(\tau_{ij})_{eff}$	Deviatory stress tensor
$\vec{J}_j$	Diffusion flux of species j

LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
CH_4	Methane
CO_2	Carbon dioxide
CO	Carbon monoxide
DR	Direct Reactor
DRI	Direct Reduce Iron
DRP	Direct Reduction Plants
EAF	Electric arc furnace
Fe	Iron
Fe_3C	Iron Carbide
Fe_2O_3	Iron (III) Oxide
H_2	Hydrogen
H_2O	Water
HBI	Hot Briquetted Iron
MBF	Mini Blast Furnace
NG	Natural Gas
PCU	Partial Combustion Unit
R&D	Research and Development
SMS	Shed and Steel Melting Shop

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND OF STUDY

The rapid development nowadays causes the high demand of steel from the heavy industry. Thus, there are many evolution on the steel making processing in order to produce the high quality steel as required, which is also environmental friendly and have low energy consumption and investment costs. The high product value is needed to ensure the steel produce has a high resistant. Natural gas and coal plays as main utilities for plant in producing steel and iron making industry. In Malaysia, Perwaja Steel Sdn. Bhd. is the leading manufacturer company of primary steel and iron product. The process started with the production of iron by reducing the oxides inside the iron ores and steel making production as the final product and distributed in various types such as billets (Perwaja Holding Berhad, 2009). The plant consists of three main parts which are Direct Reduction Plant (DRP), Direct Reduces Iron (DRI) Shed and Steel Melting Shop (SMS). This study focuses on the first component of the plant which is DRP.

Direct Reduction (DR) reactor used by this company is HYL III which is capable to producing up to 1.5 million metric tonnes of Direct Reduced Iron (DRI) per annum. The reducing agent used in processing the DRI is natural gas-based or coal-based direct reduction process. Oxygen is removed from the iron ore by chemical reactions based on Hydrogen, H_2 and Carbon Monoxide, CO for the production of DRI and Hot Briquetted Iron (HBI) (Raul & Matthias, 2002). The natural gas (NG) was firstly reformed into hot reducing gas which is known as syngas. This company is using the natural gases as a reducing agent. The natural gas will generated as self-reforming in the reduction reactor. Through the partial oxidation of natural gases and oxygen, reducing in-situ gases which are H_2 and CO will be generated. Thus, the operating temperature will increase as required for the iron ore reduction process.

In the DRP, the important unit in production of DRI is Partial Combustion Unit (PCU). PCU takes place in between the reactor and heater. The PCU consists of transfer line and two oxygen lances with nozzle attached to each of its. The transfer line is a medium to transfer the hot process gas to the reactor while the oxygen lances will supply the oxygen to the unit. The oxygen will be injected in the transfer line through the oxygen lances for partial combustion and increasing the temperature of NG. In this unit, the partial oxidation of natural gases and oxygen will generate the in-situ gases. Besides that, through this unit, the operating temperature can be increased (temperature that will enter the reactor). The high temperature of reducing gases is important in order to remove the oxides inside the iron ore to produce the DRI.

1.2 OVERVIEW OF DIRECT REDUCTION PLANT

The natural gas used was firstly reformed into hydrogen, carbon monoxide, carbon dioxide, methane, nitrogen and a little amount of water vapour. In the DRP, the gasses are reformed into single component of gas through gas reformer and then supplied to the gas heater to increase the temperature. The heated process gas is consists of high concentration of hydrogen and carbon monoxide. Then, it will partially react with the oxygen that supplied through the oxygen lances. Through this reaction, the heat of combustion will produce. The heat will increase the temperature of the process gases and reduced the energy consumption of the process to achieve the desire temperature.

Thus, many research had been carried out in propose of improving the PCU. There are several considerations that should take into account such as the need to be optimized to achieve higher Partial Combustion ratio *(Yun Li & Richard J. Fruehan et al.)*. In this research, the consideration is about the performance of PCU with one oxygen injection since the other lance is under maintenance. Besides, in the previous study, the existent of boundary refractory is neglected. Thus, in this study, the modeling of previous study has modified and boundary refractory is added to the PCU. In addition, to increasing the performance of the PCU, the different type of scheme is proposed by Research and Development (R&D) Unit in Perwaja Steel Sdn. Bhd.. Through this study, the effect of the new process scheme with current process which has different composition of process gas, velocity inlet for process gas and oxygen injected and temperature inlet of process gas was study. The details are shown is Chapter 3.

1.3 PROBLEM STATEMENT

In the PCU, the high temperature is required in order to remove the oxide inside the iron ore by the oxidation reaction between the iron ore and the NG. It is important to ensure the temperature of the system is operating at high temperature but does not exceed the fusion point of iron ore (1535^{o}C) at the reactor. Besides that, the heat transfer to the surrounding will cause the global warming. Thus, the boundary refractory material and the thickness should be identified. By performing CFD simulation, the unit performance can be investigated. Besides to identify either the boundary refractory may influence the temperature obtain or not and the amount of oxygen supplied to the unit can be investigated either the oxygen or fuel ratio can resulted in optimum performance by evaluating the temperature profile of the unit. In addition, the simulation was run by using only one lance since the other one is under maintenance.

1.4 OBJECTIVES OF STUDY

The objectives of the study are:

(i) To validate the performance of the partial oxidation unit with current installation by analyzing the profile of the temperature using CFD.

(ii) To study the effect on designing the refractory boundary toward the simulation.

(iii) To study the impact on oxygen flow rate and temperature inlet of process gas in the PCU via simulation using one operating oxygen lance.

1.5 SCOPE OF STUDY

To achieve the objectives, scopes have been identified in this training. The scope of this training is listed as below:

(i) Performing simulation on partial combustion reaction in PCU to identify the heat generated by the unit with current installation of oxygen lances with present of boundary refractory.

(ii) Comparing the impact of the amount of oxygen injected and temperature of process gas supplied in the PCU via simulation.

1.6 RATIONALE AND SIGNIFICANCE

The rationale of this study and the significance of the research are listed as below:

(i) Prevent the heat to be loss to the surrounding.

(ii) Increase the effectiveness of the system by increasing the production of DRI.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Environmental Protection Agency, 2010, the steel making process has undergoes many changes due to the most economical operating cost and the most effective production that could bring benefit for the company. Integrated steel plants produce steel from iron ore in several steps and produce very high quality steel with well controlled chemical compositions to meet all product quality requirements. In this plant, the use of furnace has identified to be the most efficient. However there are several limitations that need to be improved.

Steel is an alloy of iron that usually containing less than 1% of carbon and mostly used in the automotive and construction industries. The steel mill or also known as steel works is an industrial plant for steel manufacture. Steel is produce by two stage process. Firstly, the iron ore was reduce or smelted with coke and limestone presence in a blast furnace to produce molten iron. The molten iron will cast into pig iron or carried to the next stage which is known as steel making process. Through this process, the impurities such as sulfur, phosphorus and excess carbon will be removing. After the steel cleaned from any impurities, the alloying element will be added in order to produce the required steel (Schumacher and Sathaye, 1998).

Chunbao and Da-qiang (2010) found that, iron and steel making industry is one of the most energy-intensive industries, consuming 5% of the world's total energy consumption and emitting 3%- 4% of total world greenhouse gas emissions. The increasing of energy efficiency could be a short-term approach for the steel industry to reduce greenhouse gas emission. However, the long-term approaches to achieve a significant reduction in CO_2 emissions from the steel industry would be through developing and applying CO_2 breakthrough technologies for iron and steel making, and through increasing the use of renewable energy for iron and steel making.

Due to the energy crisis in 1970, the blast furnace was fed with iron ore continuously in order to ensure the heat can be used more efficiently. Nevertheless, the process of steel making will emit the undesired gas which is harmful to the environment. In 1995, compliance with environmental requirements was estimated to make up 20-30% of the capital costs in new steel plants (Chatterjee, 1995).

Figure 2.1 has shown the units of steel making process and related CO_2 reducing technologies. From the figure there is three path of the process. First is using the blast furnace, second is using the electric arc furnace and third is direct reduction. In the first path, the blast furnace process include the coke making, sintering and the raw material will feed to the blast furnace. Coke is a solid carbon fuel and it is used to melt and reduce iron ore. The production begins by crushing the bituminous coal. The coal is fed into a coke oven which is heated to very high temperatures for 14 to 36 hour. Heat is transferred from one oven to another in purpose of reducing the energy requirements. Then, the coke is move to a tower and cooled with water spray. After then, its move directly to an iron melting furnace or into storage for future use (Chunbao and Da-qiang, 2010).

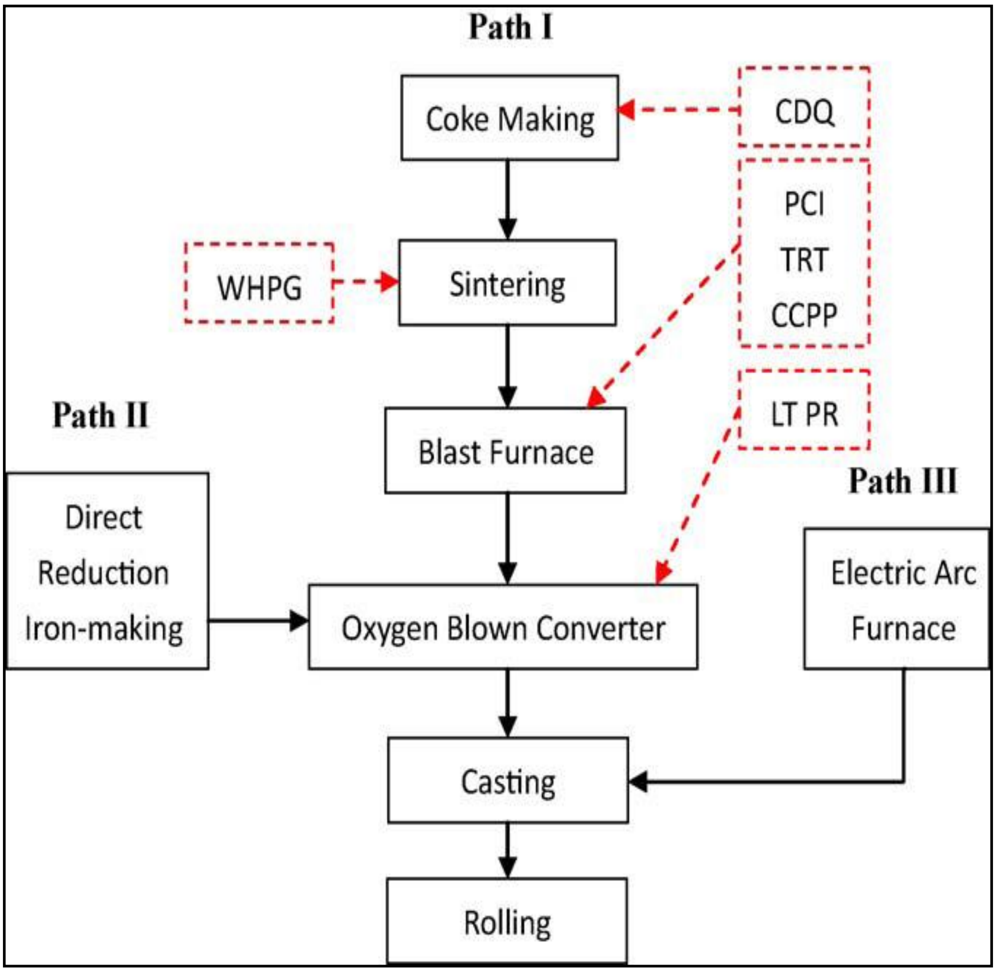

Figure 2.1: Units of steel-making process and related CO_2-reducing technologies (dot line).

Sources: Chunbao and Da-qiang, 2010

Sintering is the heating process of iron ore with flux and coke fines or coal, to produce a semi-molten mass. It is solidified into porous pieces of sinter with the size and strength characteristics necessary for feeding into the blast furnace. The raw material of making an iron will be obtained by this process. It produces extremely consistent quality in terms of its chemical composition, grain size distribution, sinter strength and reducibility on the feed. In the process, crushed coke and limestone are mixed and granulated with fine blend ore. The raw mixture is charged as a packed bed on a continuous sinter strand, the frame for holding the wood or coal in a fireplace. A burner hood mixed the coke in the mixture at the surface of the bed. Then, the combustion process will provide the heat for partial melting or solidifying which is leading to the agglomeration of the raw materials. To maintain the coke combustion, air is sucked down through the bed. The agglomerated bed also called as sinter cake is discharged at the end of the sinter strand where it is crushed and screened (Komarov and Kasai, 2004).

In this process, the particle size of the mixture has the major influence on the operation stability. Too small particles result in poor bed permeability and possible destabilizing of flame propagation. Nevertheless, using lower grade iron ores with very fine particle size has caused the need for improvement in the sintering process performance. The method that leads to an increase in the production cost but decrease in the operational efficiency or productivity and often deterioration of sinter quality is by granulation binder (Komarov and Kasai, 2004).

The blast furnace process is still the predominant iron production process, producing more than 92% of the world total iron which is unchallenged method of making hot metal on a large scale till 1990 (Chunbao and Da-qiang, 2010). Nevertheless, there are permanent disadvantages to the blast furnace process. The process was dependence on high-quality metallurgical-grade coke and iron oxide feed stocks instead of economic for only large capacities and emission of CO_2 on the coke ovens and sinter plants. Besides that, this process needs lots of assistance and supporting and cause high capital and operational intensity. Through these disadvantages, the development on iron making from blast furnace to many other alternative processes such as Shaft Furnace Direct Reduction (DR) Processes (MIDEX, HYL), Rotary Kiln DR Processes (SL/RN, CoDir, and TDR) and recently the COREX Smelting Reduction Processes.

To meet these changing needs, technology has become more prominent and integrated steel plants are being replaced with smaller plants, called mini-mills, which rely on steel scrap as a base material rather than ore. Mini-mills can never replace integrated steel plants completely because they cannot maintain the tight control over chemical composition, and thus cannot consistently produce high quality steel. Mini-mills has a narrower production line and cannot produce the specialty products produced by integrated plants. In the mid 1990, mini-mills had been identified has less than half of the quality steel market (Chatterjee, 1995).

Mini Blast Furnace (MBF) are ideally suited to small scale operations and can be viewed as a miniature version of conventional large blast furnace which is simplicity and economy. The working volume ranges between 100-370m^3 and the production capacities of hot metal between 60,000-200,000T/A. The lower grade coke and iron can be used in the small scale processes compare to the blast furnace. The products qualities from mini blast furnace are same with blast furnace. The product is also free of tramp elements which are unimportant and undesirable for the product (Joardar, 2009).

This processes use only 40-50% hot metal in Electric Arc Furnace (EAF) charge thus it help in reduce the power consumption to 380-400kwh/t liquid steel from 550-600kwh/t. Besides that, the temperature used in MBF is lower than normal blast furnace and the specific heat loss is more, the coke rate tends to be 100-160kg/thm higher (thm=ton hot metal). Nevertheless, the limitation of MBF is that coal injection is normally difficult and the higher specific heat requirement has to be met entirely by coke (Joardar, 2009).

EAF is one of the alternative methods for production of steel. This furnace does not use hot metal. It is charged with manly steel scrap. Firstly, the steel scrap will tipped into the EAF by using an overhead crane. A lid comprises of three graphite electrodes which is lowered into the EAF will carefully swung into position over the EAF. Electric current passed through the lid will forms an arc that generates heat and melts the steel scrap. During this process, other metals will be added to the steel to achieve the desire composition and oxygen is blown into the EAF in order to purifying the steel. After the checked collected sample have been done, the product will be poured off by tilled the EAF to allow the slag to float on the surface of the molten steel. After then, the EAF is tilted in the other direction and the molten steel is poured into a ladle (Metallon Holdings Limited).

The EAF consists of a large shallow bath. It is either an acid or basic lining, which are carbon electrodes over the hearth and may be raised or lowered. Current is supplied to these electrodes from special transformers. The hearth is charged with lime, and either iron ore or mill scale to remove the impurities and form a slag. The metal which forms the melt is scrapping steel of known composition. When the furnace is charged, the electrodes will be lowered and the current is switched on. The electrodes are then raised and an electric arc will jumps across from the electrodes to the metal and the melting process begins. The temperature is about 3400ºC. The furnace is tilted and the slag is ladled off. Lime, fluorspar, carbon and Ferro-alloys are added to de-oxidize and de-sulphurize the metal (Carty, 2007).

A sample is taken and tested and when the correct composition is achieved the furnace is tilted and the steel is poured into a ladle. The EAF is used to produce high grade alloy steels such as High Speed Steel, High Tensile Steel and Silver Steel. The greater control over impurities and also during the steel making is the reason this process became possible. Nowadays, it is increasingly been used in the production of common steel. Making steel process is very expensive due to the high cost of electricity. Arc furnaces range approximately one ton capacity used in foundries for producing cast iron products is up to about 400 ton units used for secondary steelmaking. Nevertheless, arc furnaces used in research laboratories and by dentists may have a capacity of only a few dozen grams (Carty, 2007).

Direct Reduction (DR) is an alternative iron source that produced by heating an iron ore which is generally contain 65-70% of iron at a high temperature but below its melting points, 1535^{o}C, utilizing Carbon Monoxide, Hydrogen and Methane (CO, H_2 and CH_4) gases and carbon-bearing materials as the reducing-carburizing agents in order to produce Direct Reduced Iron (DRI) with a porous structure or sponge iron. The demand for this process is increasing due to support the expansion of EAF steelmaking for production of new high quality product. This process is more environmental friendly in contrast with the blast furnace because they do not require high quality metallurgical-grade coke and iron oxide feed stocks but usually use fines and fine coal directly by avoiding step agglomeration and coking. The potential of decreasing the CO_2 had been determine to be 20%. **Figure 2.2** has shown the statistic data about the formation of CO_2 gasses in the blast furnace, coke making, sintering, pelletizing and steel making itself (Zeng, et al, 2009).

DR processes can be dividing into two reducing agent source, natural gas-based direct reduction process and coal-based direct reduction process. The primary DRI production processes are the natural gas-based direct reduction processes such as MIDREX and HYL using shaft furnace, and FINMET using fluidized bed. The two-stage hydrogen-based Circored process using a circulating fluidized bed system to reduce iron. The process uses pure hydrogen produced from natural gas by steam-reforming and CO shift reactions, where the highly concentrated CO_2 by product could be easily disposed by sequestration (Chunbao and Da-qiang, 2010).

The iron ore will be passed through several processes in the DRP. Before becoming a final product, the raw material (iron ore) must be cleaned from oxides and the process of removing the oxides is using hot reducing gases, which are Hydrogen and Carbon Monoxide gases. In the presence of high temperature of reducing gases, the additional energy is generated to the system. Firstly, the NG was passed through reformation process at high temperature of about 930^{o}C or 1203 K. Then, from the self-reformation process, the reducing gases are generated in the reduction reactor, feeding natural gases as make-up to the reducing gas circuit and Oxygen injection at the inlet of the reactor. **Figure 2.3** describe the HYL process in detail. From **Figure 2.4**, the position of oxygen injection is shown at certain position on the transfer line.